Nuclear radiations

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UNIVERSITAS BUDAPESTINENSIS DE SEMMELWEIS NOMINATA · 1769

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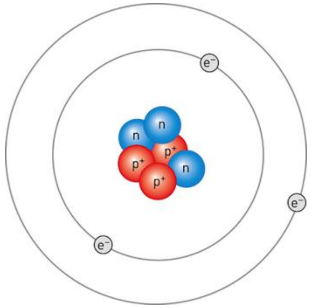


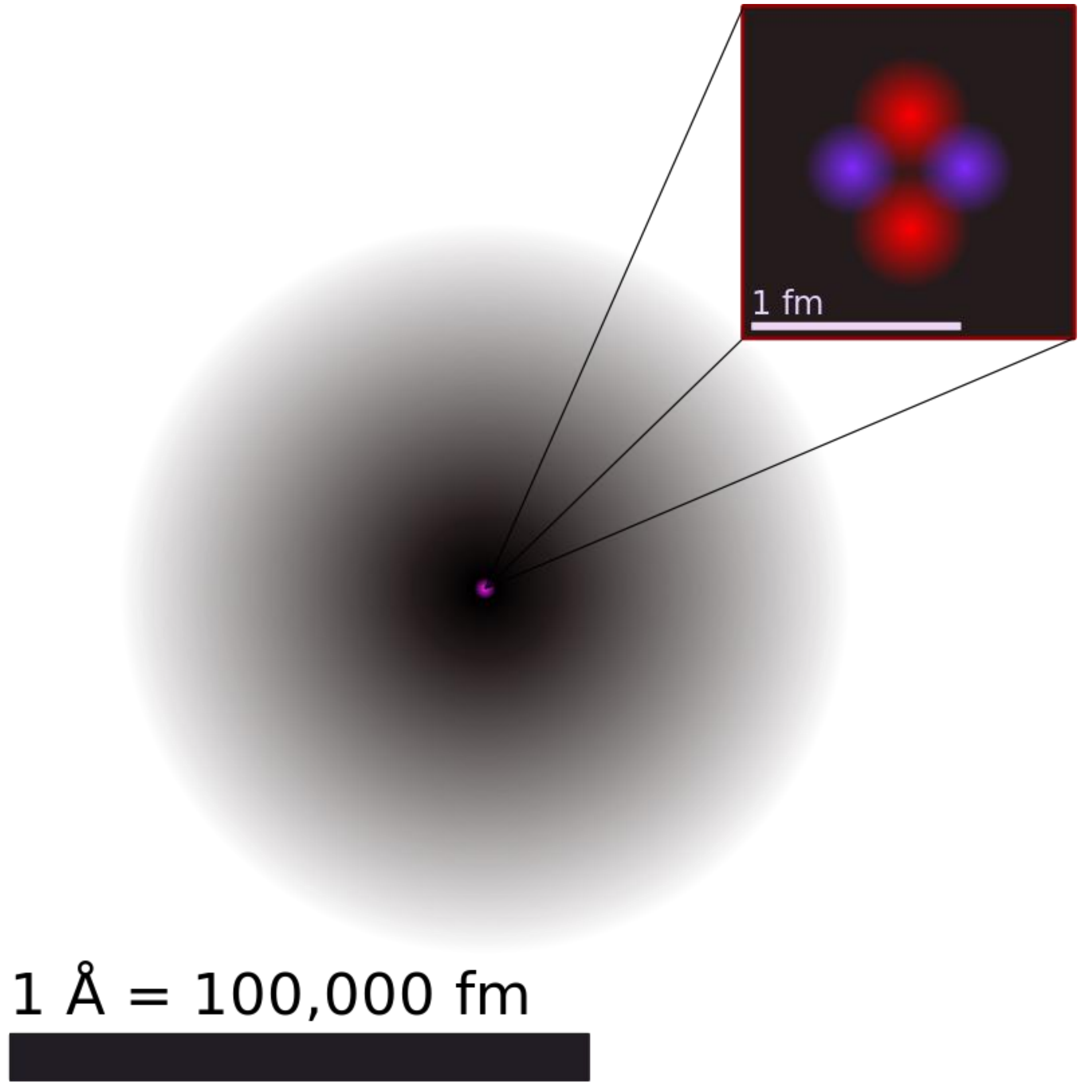
Constituents of atoms

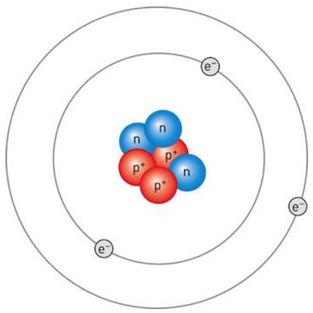
Particle	**Symbol**	**Resting Energy (MeV)**	**Relative Charge***	**Mass (kg)**	**Relative Mass (AMU)****
electron	e	0.51100	1-	9.11×10^{-31}	$5.4858\text{X}10^{-4}$
proton	p	938.272	1+	$1.6726\text{X}10^{-27}$	1.0072765
neutron	n	939.566	0	$1.6749\text{X}10^{-27}$	1.0086649

***** electrons have an electric charge of -1.602×10^{-19} C

******The atomic mass unit is defined as 1/12 of the carbon (^{12}C) atom

Nucleus size



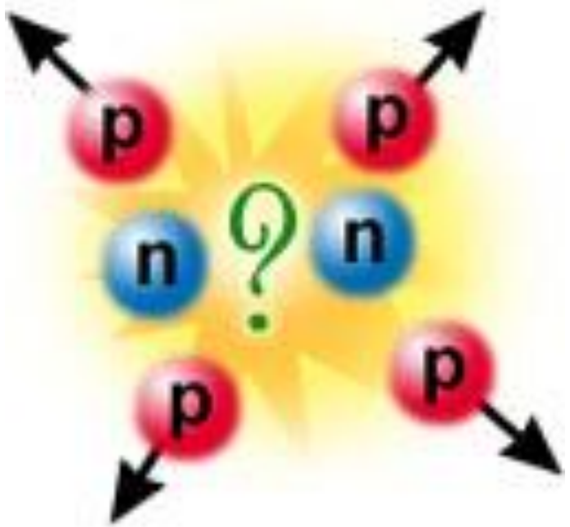


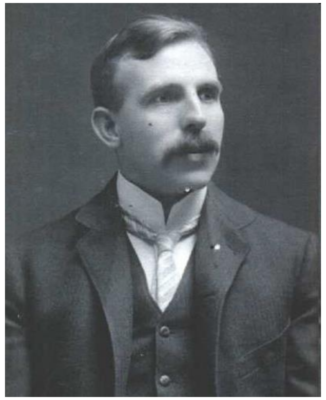
Nuclear stability

There are very large *repulsive electrostatic forces* between protons

should cause the nucleus to fly apart

It must be an attractive force be present within the nucleus!





Rutherford, 1911 – **nuclear force:**
an attractive force acting on short distances within the nucleus, independent of charges, and stronger than the Coulomb forces.

The hypothesis of neutron (discovered by Chadwick in 1932)

Nuclear notation

Mass number
$A = Z + N$

$$^{A}_{Z}X$$

Chemical symbol for the element

Atomic number = Number of protons

$$^{27}_{13}\mathrm{Al}$$

N = number of neutrons

nucleon = proton or neutron

Nuclear stability

$$\Delta M = [Zm_p + (A-Z)m_n] - M(A,Z)$$

The mass defect (or mass deficit) problem: the mass of a nucleus is less than the mass of its constituent nucleons. The difference can be explained by Einstein's law of mass-energy equivalence:

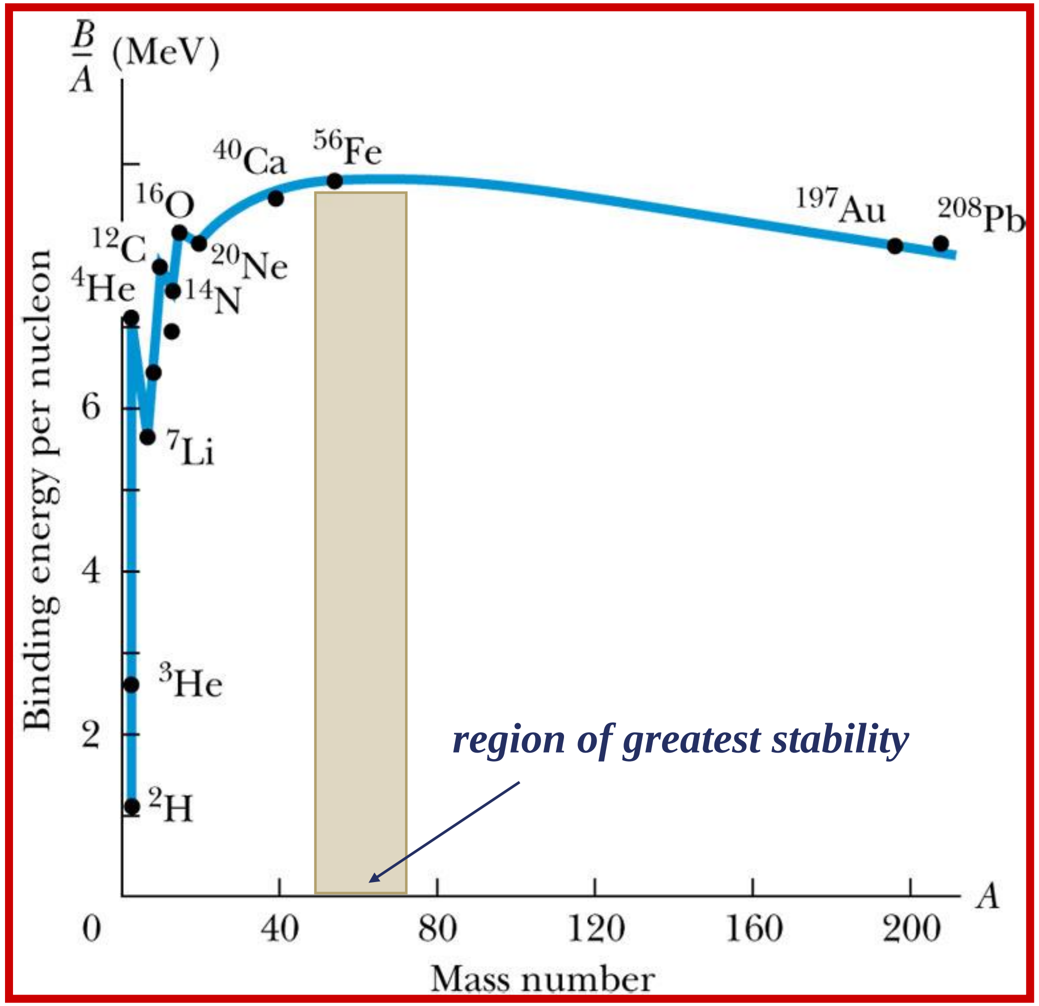
$$\boxed{\Delta E = \Delta M c^2}$$

The energy corresponding to the mass defect is the binding energy of the nucleons.

Binding energy per nucleon

- The curve increases rapidly
- Sharp peaks for the even-even nuclei for $^{4}_{2}He$, $^{12}_{6}C$, and $^{16}_{8}O$
- Maximum is around A=56

nucleon = proton or neutron



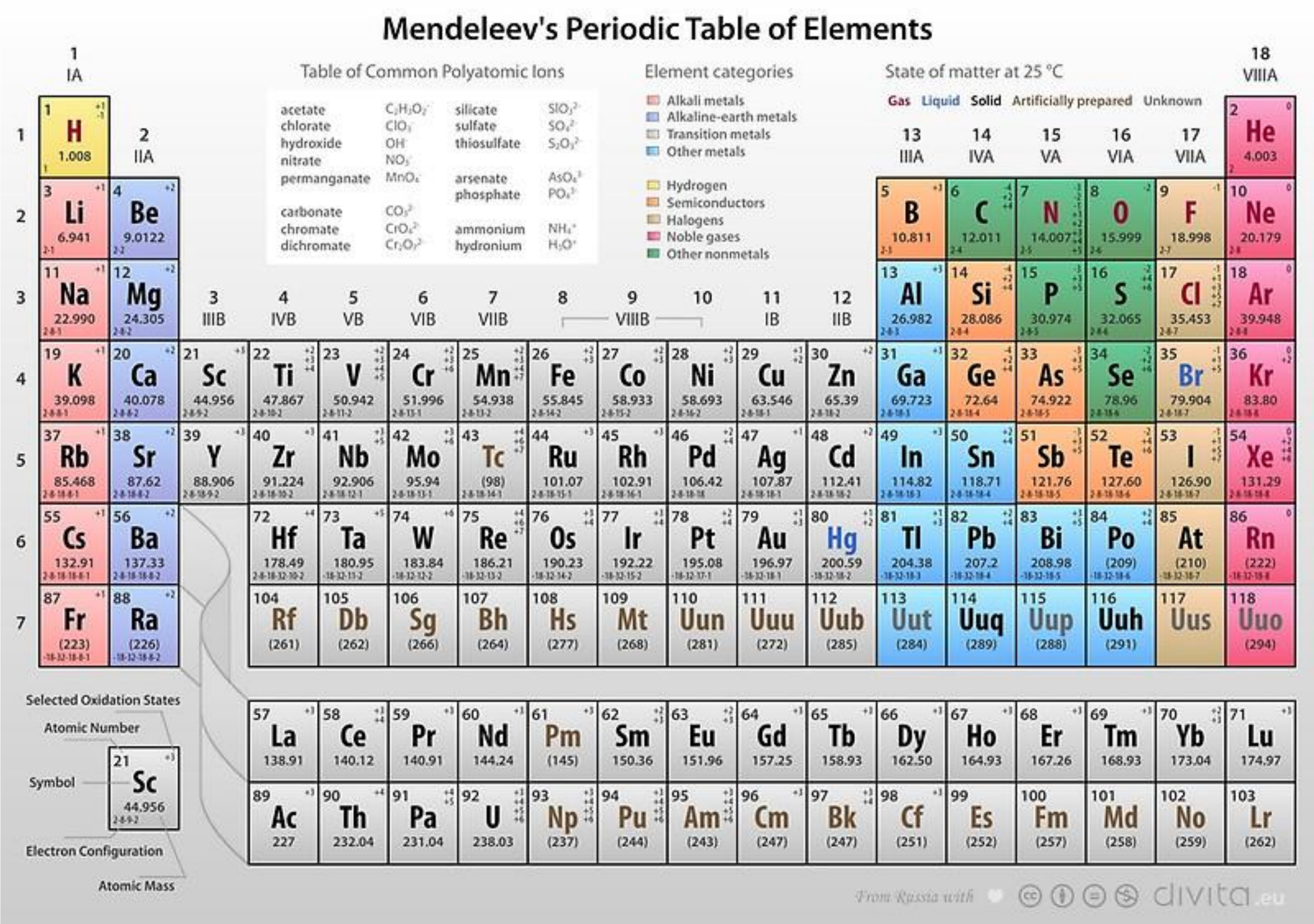
Isotopes

Greek ***isos topos* = *equal place***

Isotopes of an element have nuclei with

- the same number of protons
- different numbers of neutrons
- different mass number

isotope = same place = same atomic number



Mendeleev's Periodic Table of Elements

Table of Common Polyatomic Ions

acetate	$C_2H_3O_2^-$	silicate	SiO_3^{2-}
chlorate	ClO_3^-	sulfate	SO_4^{2-}
hydroxide	OH^-	thiosulfate	$S_2O_3^{2-}$
nitrate	NO_3^-		
permanganate	MnO_4^-	arsenate	AsO_4^{3-}
		phosphate	PO_4^{3-}
carbonate	CO_3^{2-}		
chromate	CrO_4^{2-}	ammonium	NH_4^+
dichromate	$Cr_2O_7^{2-}$	hydronium	H_3O^+

Element categories
- Alkali metals
- Alkaline-earth metals
- Transition metals
- Other metals
- Hydrogen
- Semiconductors
- Halogens
- Noble gases
- Other nonmetals

State of matter at 25 °C

Gas Liquid Solid Artificially prepared Unknown

	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 H 1.008																	2 He 4.003
2	3 Li 6.941	4 Be 9.0122											5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.179
3	11 Na 22.990	12 Mg 24.305											13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.065	17 Cl 35.453	18 Ar 39.948
4	19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.867	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.64	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.80
5	37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.90	54 Xe 131.29
6	55 Cs 132.91	56 Ba 137.33		72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra (226)		104 Rf (261)	105 Db (262)	106 Sg (266)	107 Bh (264)	108 Hs (277)	109 Mt (268)	110 Uun (281)	111 Uuu (272)	112 Uub (285)	113 Uut (284)	114 Uuq (289)	115 Uup (288)	116 Uuh (291)	117 Uus	118 Uuo (294)

57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
89 Ac 227	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

From Russia with ♥ divita.eu

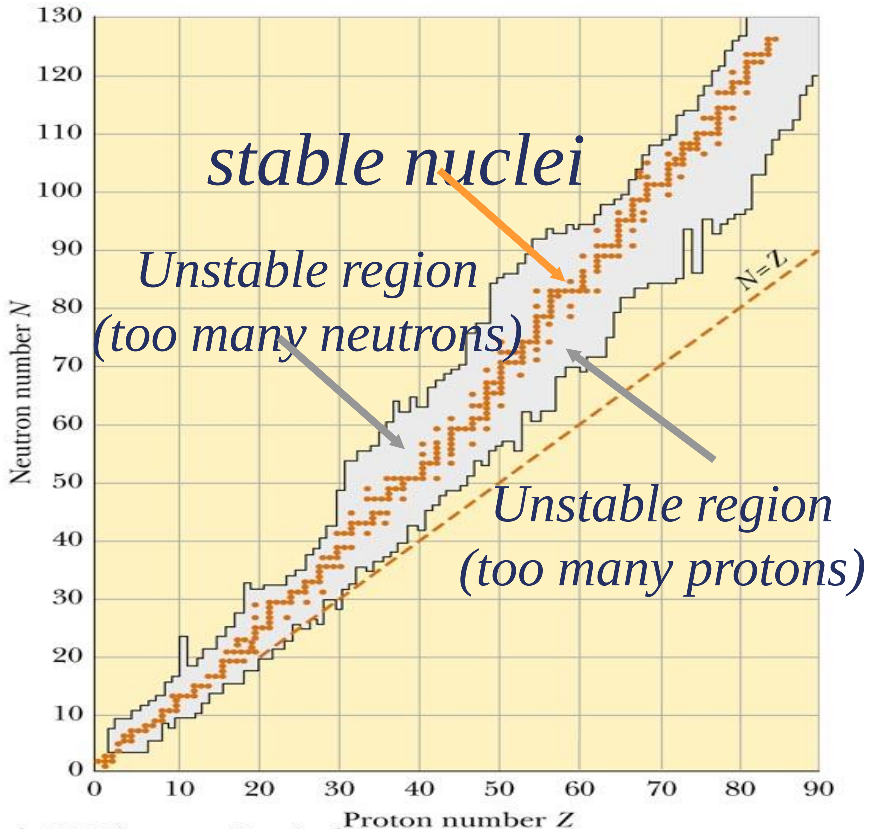
Nuclear stability chart

- Light nuclei are most stable if
  N=Z

- Heavy nuclei are most stable when
  N > Z

As the number of protons increases, the Coulomb force increases and so more neutrons are needed to keep the nucleus stable

- No nucleus is stable when Z > 83



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What does it mean „unstable”?

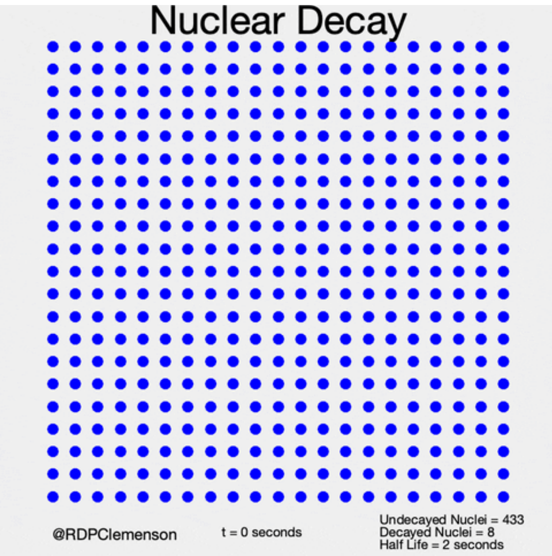
Radioactive decay

Antoine Becquerel
1903 Nobel Prize in Physics for discovering radioactivity

Image of Becquerel's photographic plate which has been fogged by exposure to radiation from an uranium salt. The shadow of a metal Maltese Cross placed between the plate and the uranium salt is clearly visible. (1896)

Radioactive decay

- ***Radioactivity*** is the **spontaneous release of energy** in the form of particles or electromagnetic waves
- Experiments suggested that radioactivity was the result of the decay of **unstable nuclei**
- Three types of radiation can be emitted
  - Alpha (α) particles
  - Beta (β) particles
  - Gamma (γ) rays



- it is a *statistical process* – individual disintegrations occur ***randomly***
- it results in a **decrease over time** of the initial number of unstable (radioactive) nuclei

Characteristics of radioactive decay

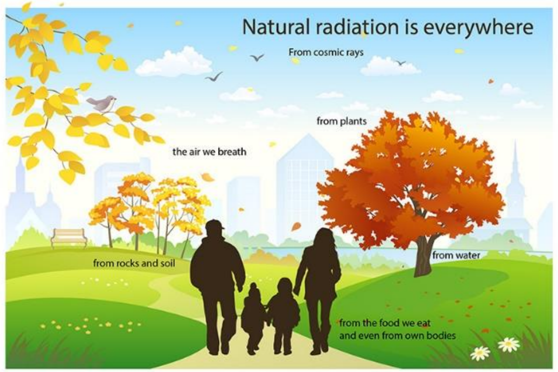
Activity: $$\Lambda = \left|\frac{\Delta N}{\Delta t}\right|$$

N: number of nuclei to be decayed
t: time

Activity = number of nuclei decayed in a unit time

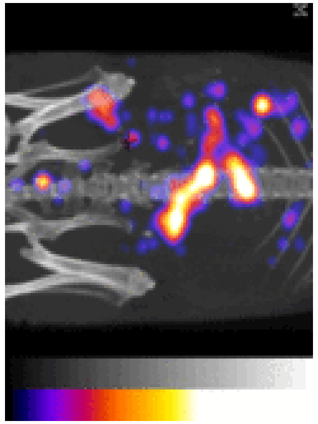
unit: becquerel (Bq)   1Bq = 1 decay/sec

background



kBq,

diagnostics

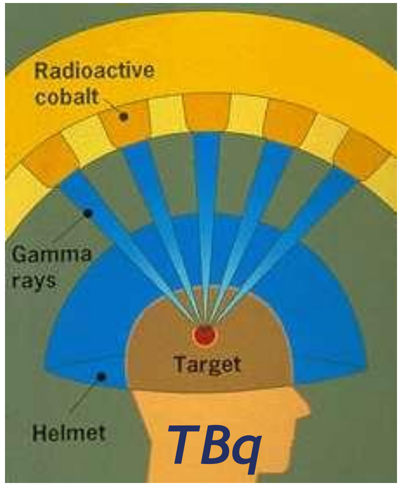


MBq,

laboratory practice

GBq,

therapy



TBq

Radioactive decay law

Differential form:

$$\left|\frac{\Delta N}{\Delta t}\right| = -\lambda N$$

solution

λ: decay constant, characteristic for isotopes (1/s)

Integral form:

$$N = N_0 e^{-\lambda t}$$

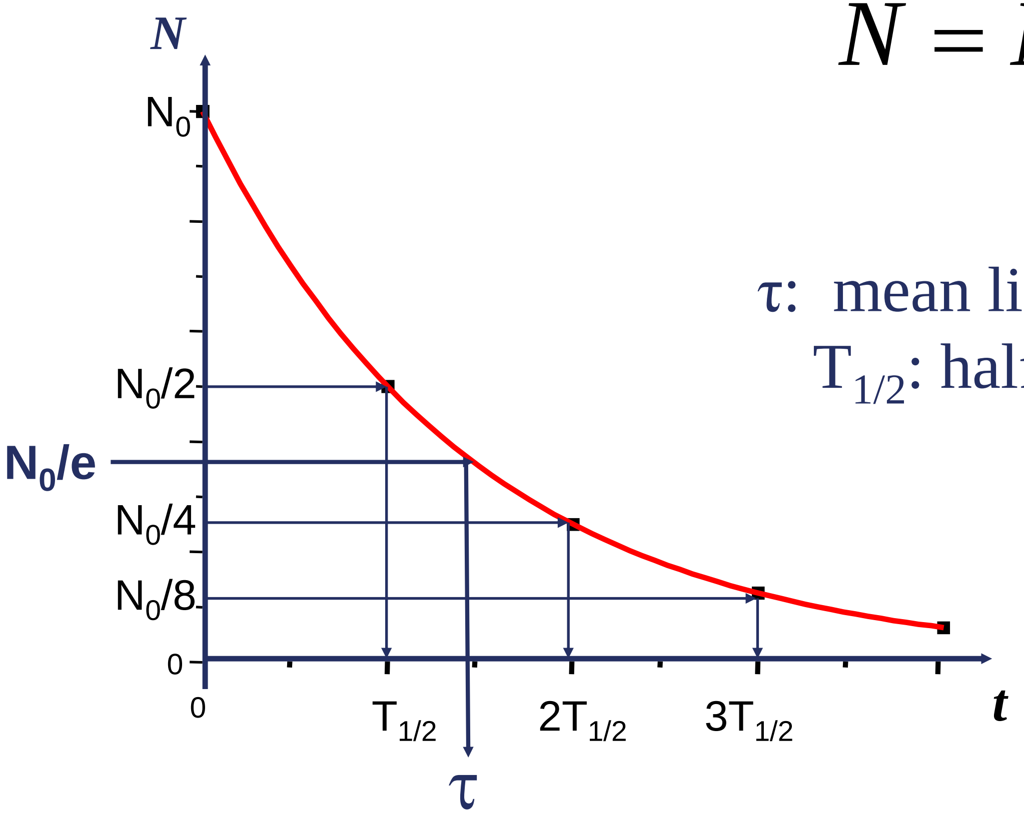
N_0: number of radioactive nuclei at t=0,
N: number of remaining radioactive nuclei at a later time t

Activity depends both on the type of isotope and on the size of the population of unstable (radioactive) nuclei

Specific activity: activity in a unit mass of isotope (Bq/kg)

Graphical representation

$$N = N_0 e^{-\lambda t}$$



τ: mean life time

$T_{1/2}$: half-life

If t = τ

$$\downarrow$$

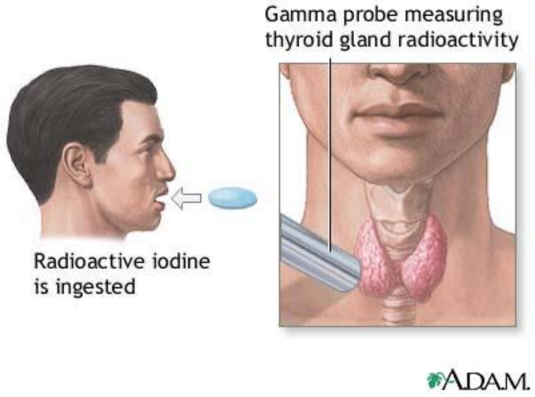
$$N_0 / e = N_0 e^{-\lambda\tau}$$

$$\downarrow$$

$$\lambda = \frac{1}{\tau}$$

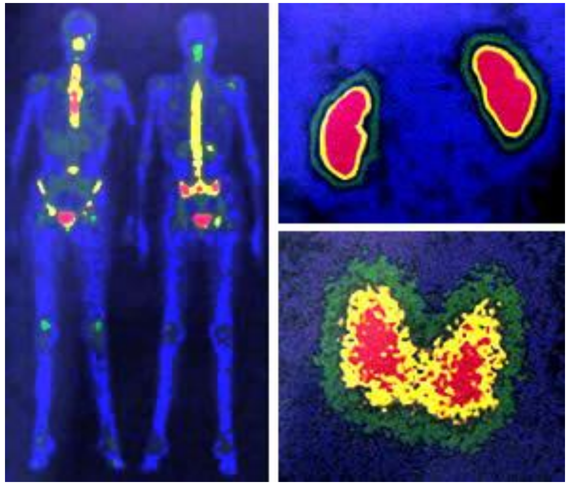
If t = $T_{1/2}$ $\longrightarrow$ $N_0 / 2 = N_0 e^{-\lambda T_{1/2}}$ $\longrightarrow$ $\lambda = \frac{\ln 2}{T_{1/2}} = \frac{0.693}{T_{1/2}}$

Half-lives in Medical Practice



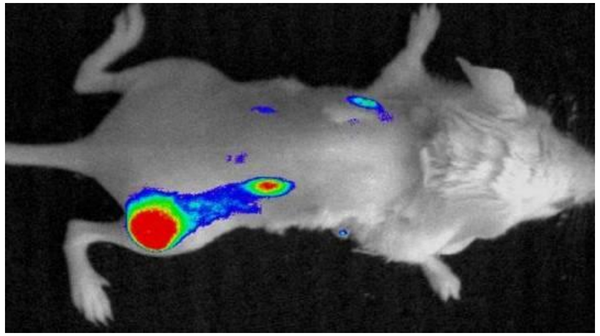
Iodine - 131 (^{131}I) - $T_{1/2}$ = 8 days

Thyroid treatment



Technetium-99m (^{99m}Tc) - $T_{1/2}$ = 6 hours

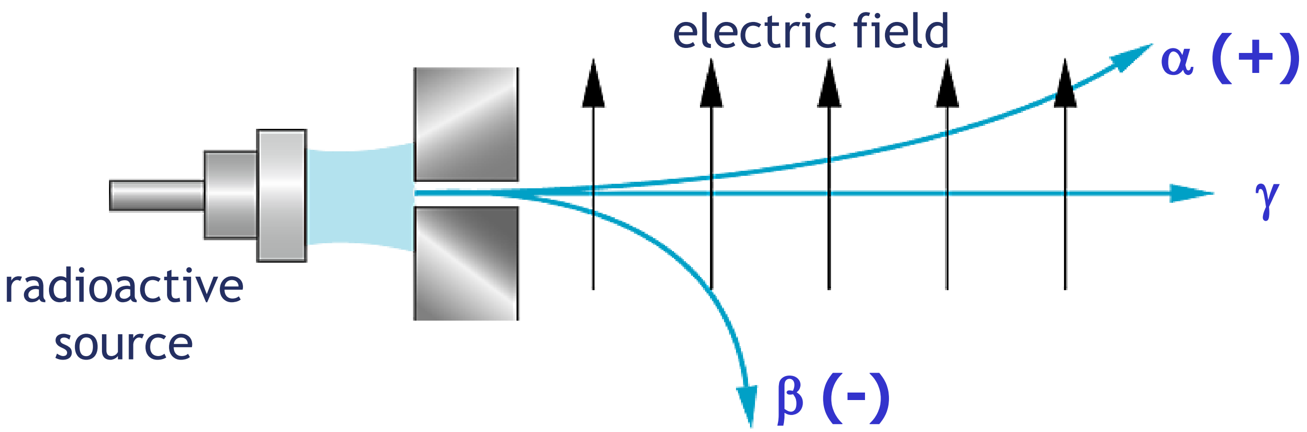
Isotope diagnostics

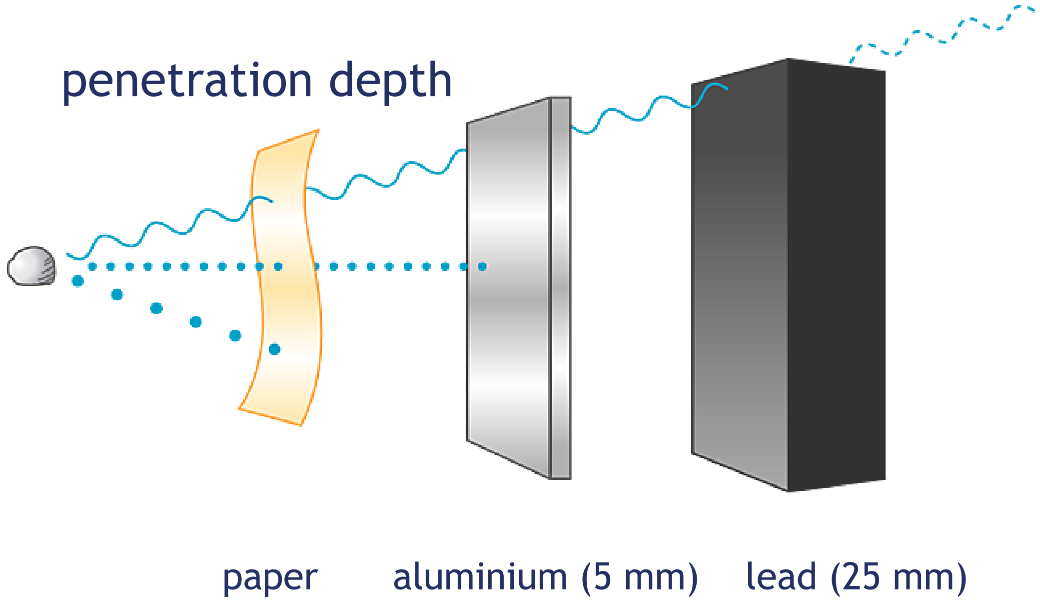


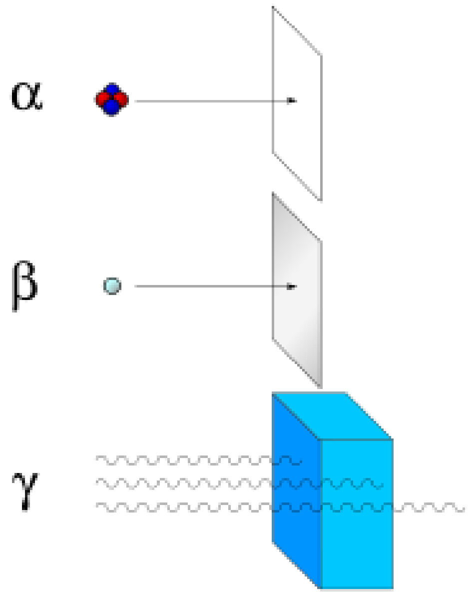
Gold-198 (^{198}Au) - $T_{1/2}$ = 2.7 days

Tumor therapy

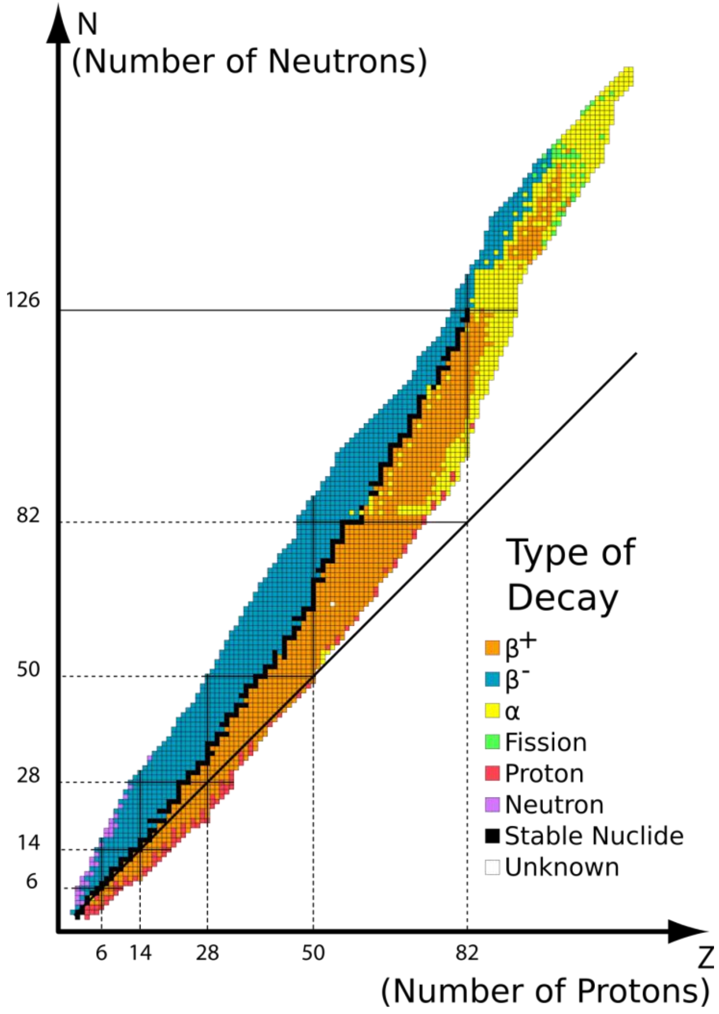
Types of radioactive decay

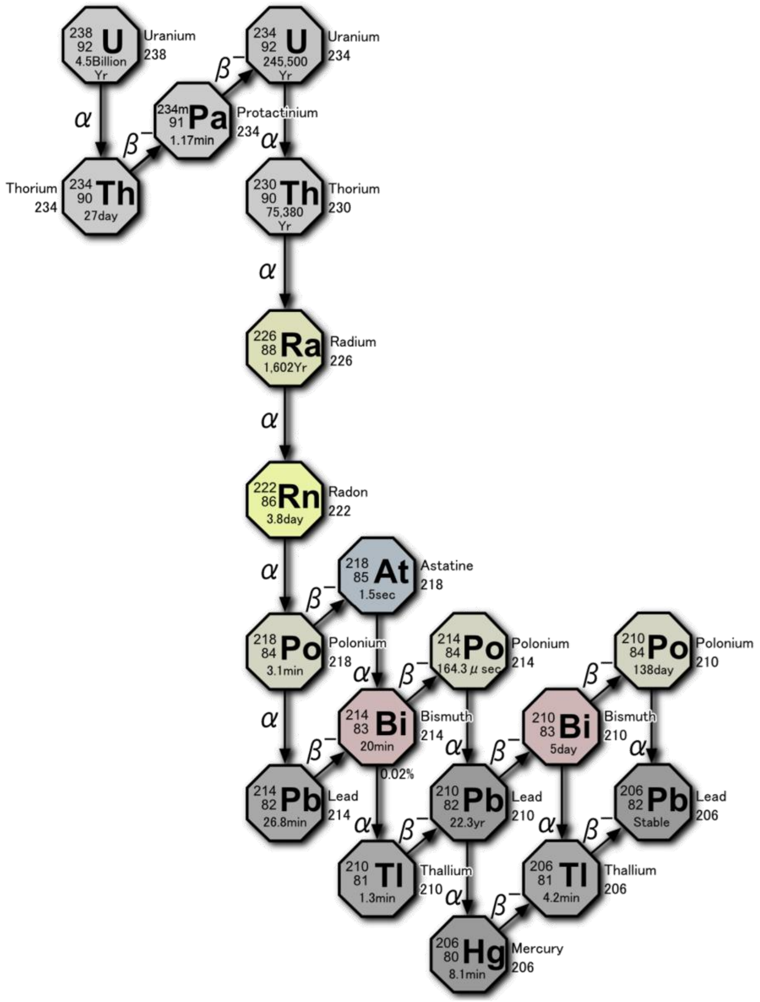




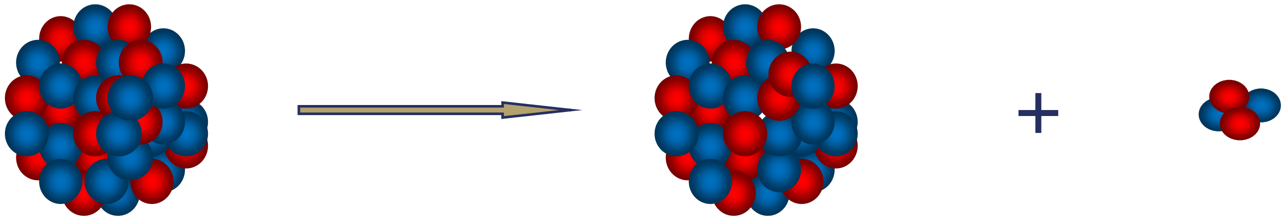


Types of radioactive decay





α decay



parent nucleus *daughter nucleus* *α particle*

$${}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$$

α **particle** is a nucleus of helium containing **two neutrons and two protons**

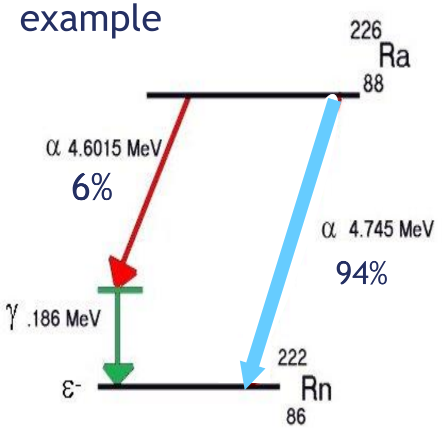
Heavy nuclei (A > 150) can disintegrate by emission of an a particle

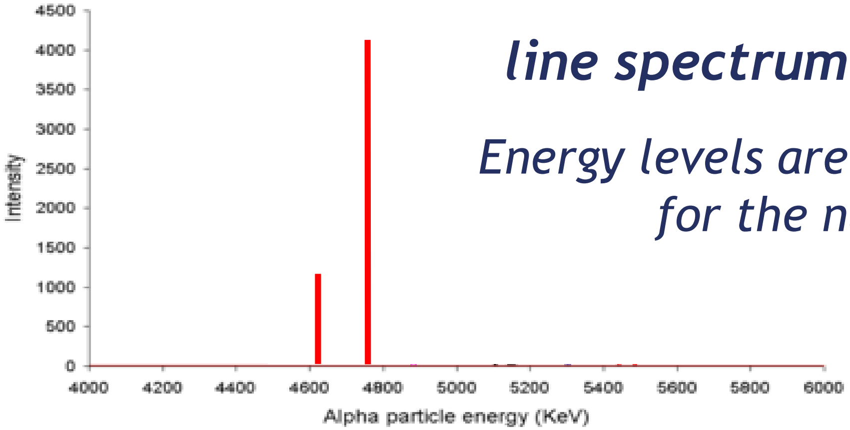
example:

$${}^{226}_{88}Ra \longrightarrow {}^{222}_{86}Rn + {}^{4}_{2}\alpha$$

Energy spectrum, penetration depth, application of α radiation

example

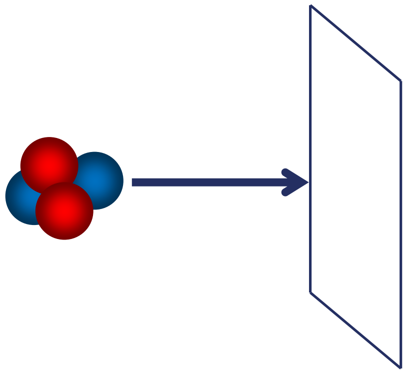




line spectrum

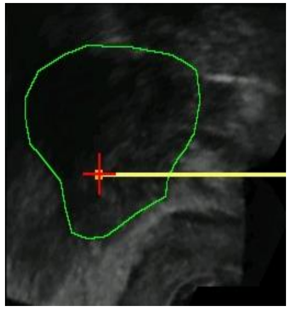
Energy levels are characteristic for the nucleus

absorber	**density**	**alpha range**
air (STP)	1.2 mg/cm^3	**3.7 cm**
paper (20lb)	0.89 g/cm^3	**53 µm**
water (soft tissue)	1.0 g/cm^3	**45 µm**

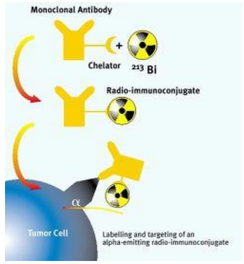


Diagnostics: none!!!

Targeted alpha **therapy** of cancer



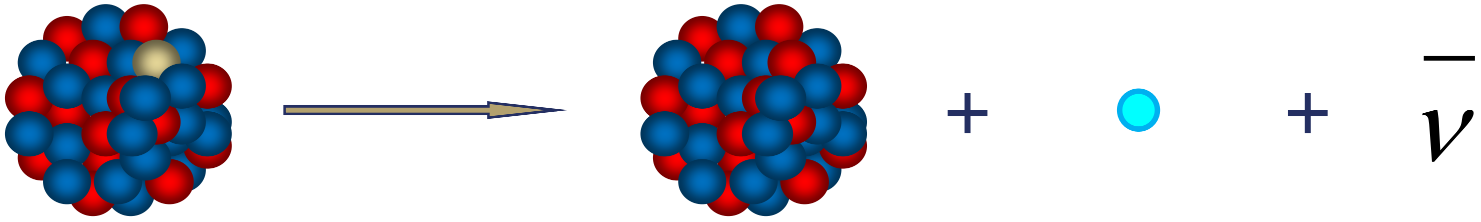
Seed implantation by needle



Monoclonal antibody

β decay

1. Neutron excess: β⁻ decay



parent nucleus *daughter nucleus* *electron* *anti-neutrino*

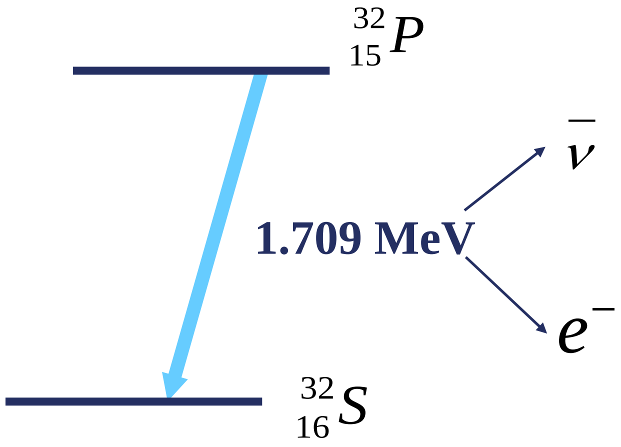
$$^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + e^{-} + \bar{\nu}$$

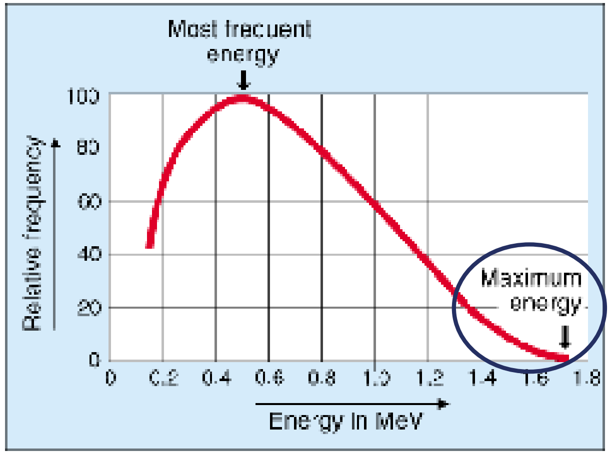
$$^{1}_{0}n \longrightarrow {}^{1}_{1}p^{+} + e^{-} + \bar{\nu}$$

example:

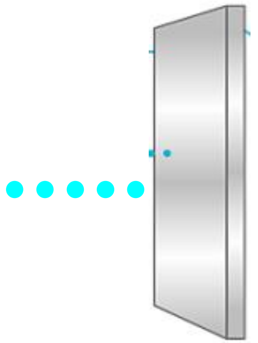
$$^{131}_{53}I \longrightarrow {}^{131}_{54}Xe + e^{-} + \bar{\nu}$$

Energy spectrum, penetration depth, application of β- **radiation**





continuous spectrum
with a maximum kinetic energy for the ß particle

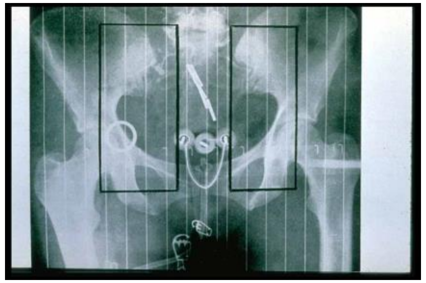


5 mm Al

absorber	***density***	***maximum beta range***	
		(2.3 MeV)	*(1.1 MeV)*
air	1.2 mg/cm^3	8.8 m	3.8 m
water (soft tissue)	1.0 g/cm^3	11 mm	4.6 mm
aluminum	2.7 g/cm^3	4.2 mm	2.0 mm
lead	11.3 g/cm^3	1.0 mm	0.4 mm

Diagnostics: **none!!!**

Targeted therapy: hyperthyroidism, thyroid, prostate, and several other types of cancer

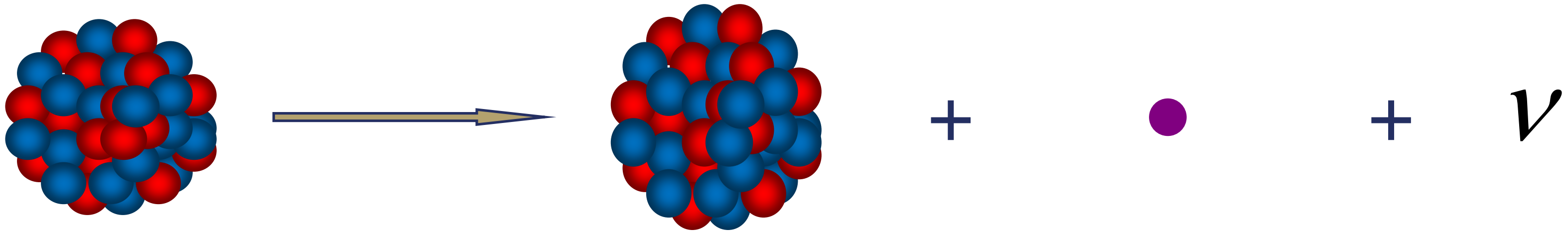


Brachytherapy: implants into the tumours

Endovascular irradiation

β decay

2. Proton excess: β⁺ decay



parent nucleus *daughter nucleus* *positron* *neutrino*

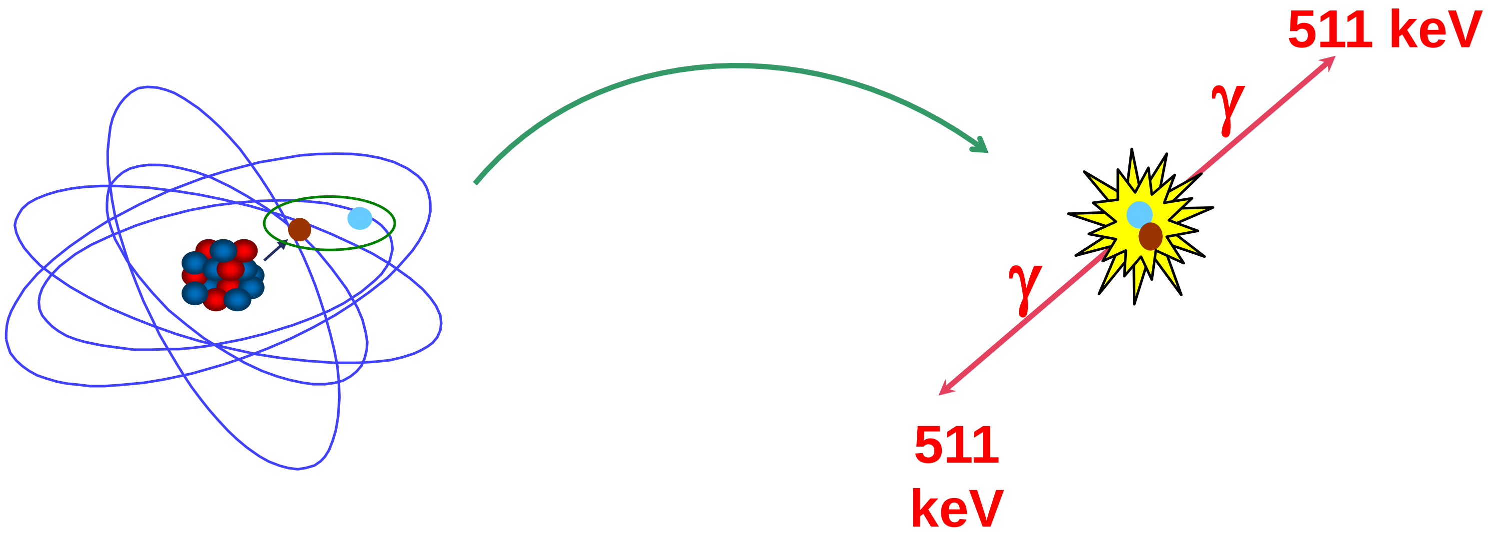
$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y + e^{+} + \nu $$

$$ {}^{1}_{1}p^{+} \longrightarrow {}^{1}_{0}n + e^{+} + \nu $$

example:

$$ {}^{11}_{6}C \longrightarrow {}^{11}_{5}B + e^{+} + \nu $$

Annihilation - particle-antiparticle pairs annihilate each other



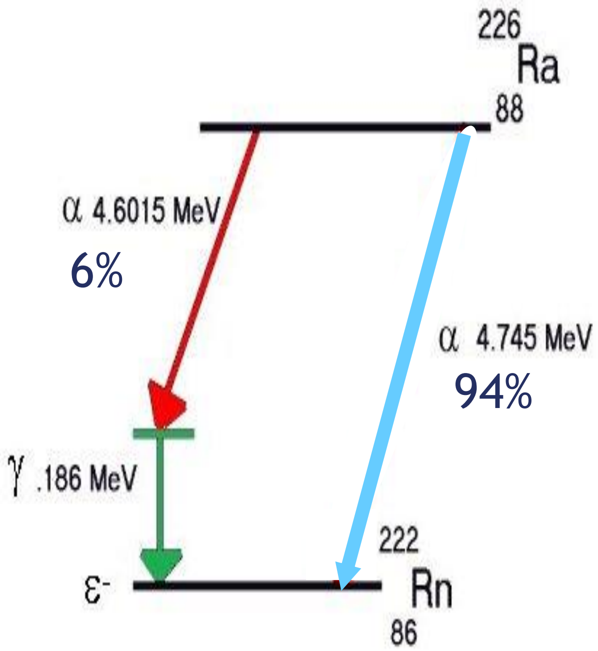
1. Conservation of momentum: two γ photons with opposite direction are produced

2. Energy balance:

$$m_e c^2 + m_p c^2 = 2\,hf$$

mass-energy equivalence

γ decay – Isomeric transition



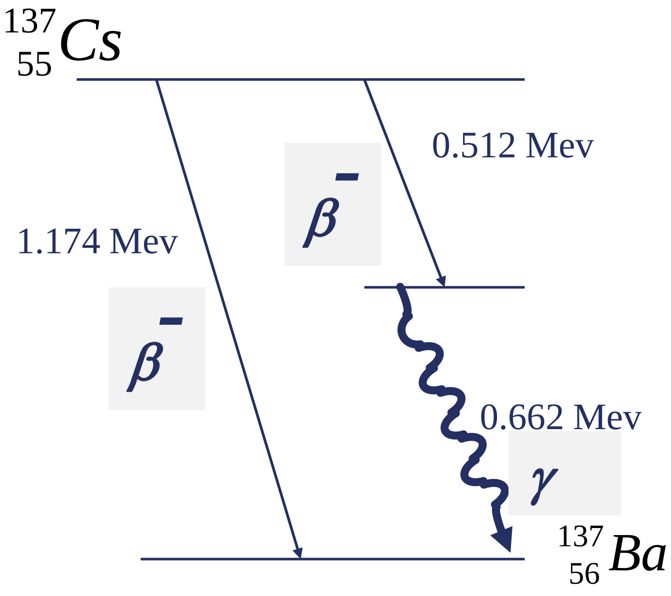
Sometimes the newly formed isotopes (after α or β decay) appear in the excited state.

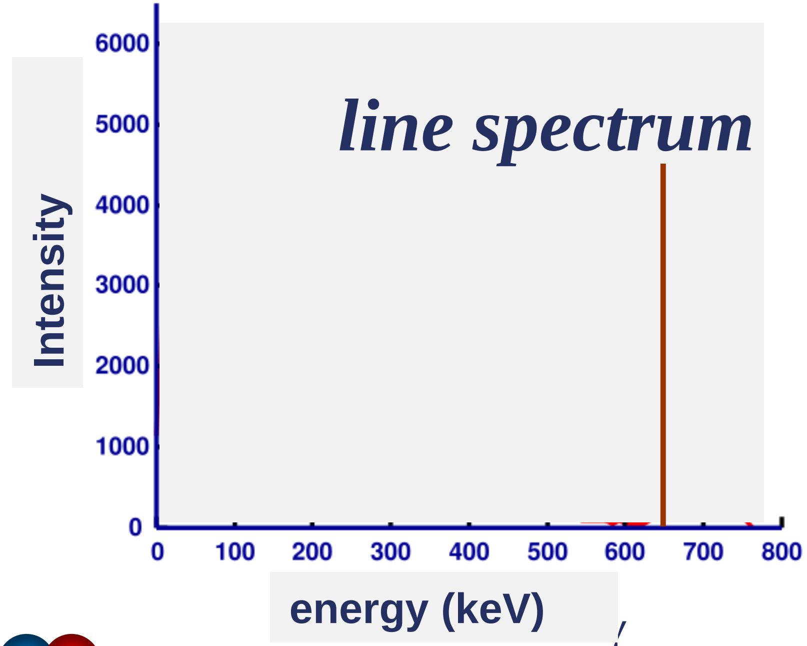
Excited nuclides release the excess of energy by emission of gamma rays.

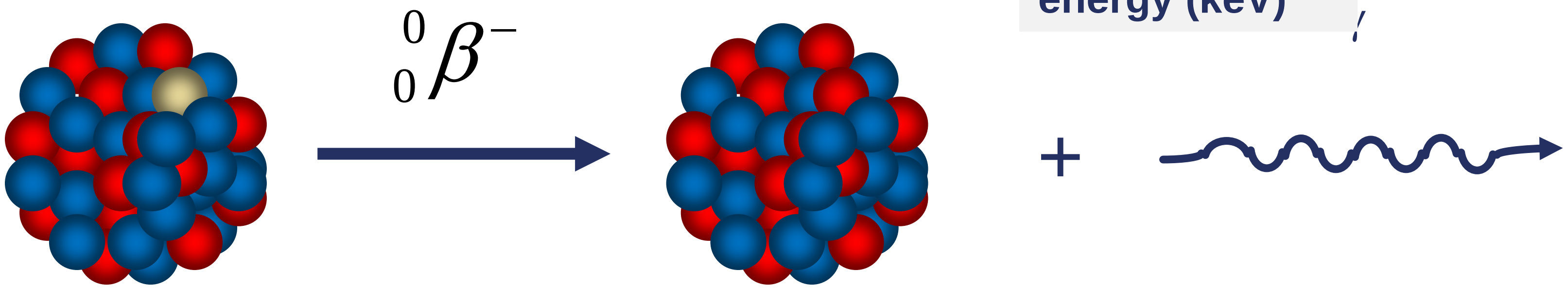
half-life ranging from hours up to more than 600 years

$${}^{Am}_{Z}X \rightarrow {}^{A}_{Z}X + \gamma$$

Energy spectrum of γ radiation



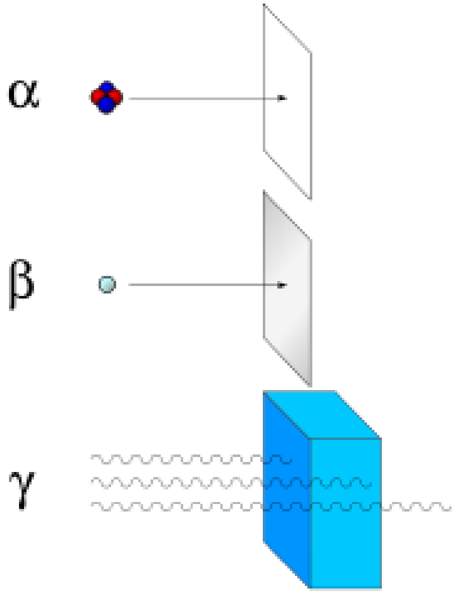




parent nucleus *daughter nucleus* *gamma Ray*

Energy is characteristic for the nucleus

Penetration depth of γ radiation



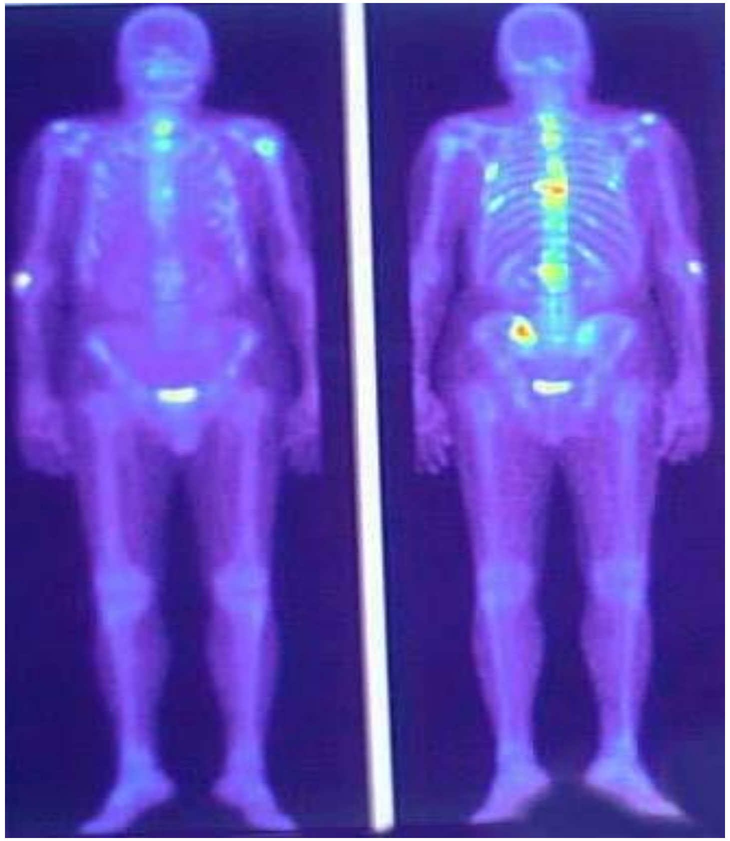
lead (25 mm)

Penetration depth is higher than that of α or ß particles, but it is highly energy dependent.

Gamma rays can travel hundreds of meters in the air and can easily pass through the human body (~dm).

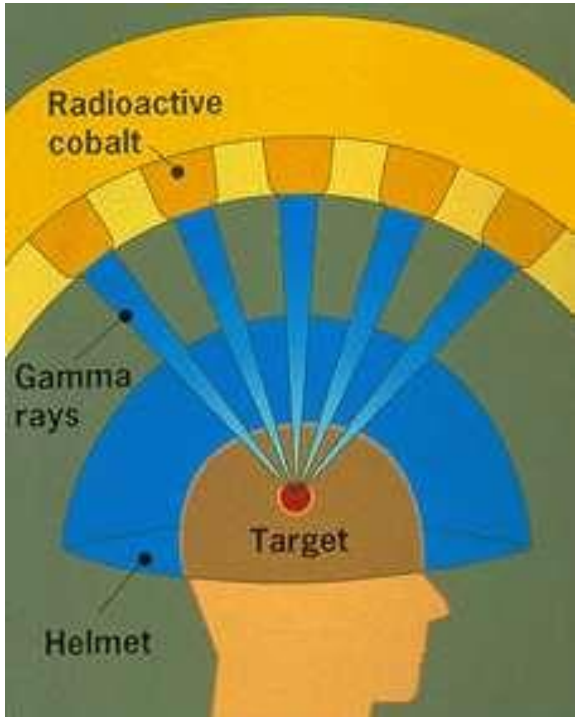
Medical application of γ rays

Diagnostics:
ideal for isotope diagnostics



Bone scan using ^{99m}Tc labeled phosphate compound

Therapy: γ-knife



TBq

Checklist

Composition and stability of the nucleus

Origin of nuclear force

Radioactive decay law – differential and integral form

Decay constant, half-life, mean life time

Types of nuclear radiation and their characteristics